Hydrodynamic Flow in PbPb Collisions Observed via Azimuthal Angle Correlations of Charged Hadrons

Eric Appelt for the CMS Collaboration

Vanderbilt University, 6301 Stevenson Center, VU Station B No.351807, Nashville, TN 37235, United States

Abstract. Azimuthal angle correlations of charged hadrons were measured in $\sqrt{s_{NN}}=2.76$ TeV PbPb collisions by the CMS experiment. The distributions exhibit anisotropies that are correlated with the event-by-event orientation of the reaction plane. Several methods were employed to extract the strength of the signal: the event-plane, cumulant and Lee-Yang Zeros methods. These methods have different sensitivity to correlations that are not caused by the collective motion in the system (non-flow correlations due to jets, resonance decays, and quantum correlations). The second Fourier coefficient of the charged hadron azimuthal distributions was measured as a function of transverse momentum, pseudorapidity and centrality in a broad kinematic range: $0.3 < p_T < 12.0$ GeV/c, $|\eta| < 2.4$, as a function of collision centrality. In addition, the third through sixth Fourier components were measured at midrapidity using selected methods.

Keywords: Relativistic Heavy Ion Collisions, Elliptic Flow, Hydrodynamic Flow

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INTRODUCTION

In non-central heavy ion collisions, the initial spatial asymmetry of the collision zone leads to anisotropies in the final state charged hadron emission. This collective behavior is known as "flow" and is the result of the hydrodynamic expansion of the matter produced in the collision zone and is driven by uneven pressure gradients. The strength of this flow is measured through a Fourier expansion of the charged hadron azimuthal distributions with respect to the reaction plane, defined by the impact parameter vector and collision direction. The strength of the flow can be related to the transport properties of the strongly interacting medium produced in the collision.

The second Fourier coefficienct (v_2) has been studied extensively, while higher harmonics are more challenging due to smaller signals. Although the odd-order harmonics, v_3 and v_5 , have been expected to vanish due to the symmetry of the collision system assuming a smooth spacial eccentricity profile, the geometric fluctuations of the positions of nucleons in the colliding nuclei may produce event-by-event fluctuations in the initial eccentricity resulting in odd-order harmonics in the final state [1].

Extracting the transport coefficients of the strongly coupled quark-gluon plasma from measured flow is difficult as the initial state can only be described by theoretical modeling. Different models of the initial state of the collision lead to different predictions for the strength of the flow given the same shear and bulk viscosities of the medium [2]. Additionally, the various methods applied in the experimental determination of the azimuthal anisotropies have varying sensitivities to "non-flow" azimuthal correlations, such as resonance decays and jets.

EXPERIMENTAL METHODS

First results on elliptic and higher order flow of charged hadrons measured in PbPb collisions at $\sqrt{s_{NN}}=2.76$ TeV are reported. The analysis was performed using 2.31 million events selected by a minimum-bias trigger requiring a coincidence between signals in the two forward hadronic calorimeters or the beam scintillator counters with an estimated trigger efficiency of $(97\pm3)\%$ of the total inelastic cross section. Further offline event selection was applied to remove beam-halo and beam-gas events, and to limit variations in tracking efficiency at high pseudorapidity. The v_n coefficients were measured using the CMS tracker comprised of silicon pixel and strip detectors covering a pseudorapidity range of $|\eta| < 2.4$. Low transverse momentum particles $(0.3 < p_T < 1.8 \text{ GeV/c})$ were reconstructed using only the pixel detectors, while higher transverse momentum particles $(p_T > 1.5 \text{ GeV/c})$ were reconstructed using the full tracker. A detailed description of the CMS detector [3] is found elsewhere.

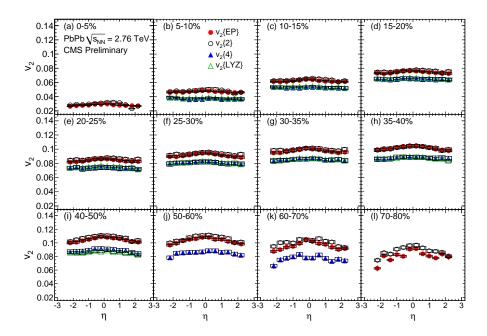


FIGURE 1. Comparison of the four methods for determining v_2 as a function of pseudorapidity η for the 12 centrality classes. The v_2 signal has been integrated over a transverse momentum range of $0.3 < p_T < 3.0$ GeV/c. The error bars show the statistical uncertainties, and the boxes represent the systematic uncertainties.

The elliptic flow (v_2) analysis [4] was performed with the event plane method [5], 2 and 4-particle cumulant method [6, 7], and the Lee-Yang zeros (LYZ) method [8, 9]. Higher order flow $(v_3$ through v_6) analysis [10] was performed with select methods. The odd harmonics, v_3 and v_5 , were measured using the 2-particle cumulant method. Additionally, the fourth harmonic, v_4 was measured using the LYZ method and 3 and 5-particle cumulant methods, and the sixth harmonic, v_6 was measured using the LYZ method.

For the event plane method, elliptic flow was measured with respect to event planes determined from tracks in the backward $(-2 < \eta < -1)$ and forward $(1 < \eta < 2)$ pseudorapidity regions. This provides a gap of $1 < \Delta \eta < 3.4$ between the tracks used in the elliptic flow measurement and those used in the event plane determination, which is expected to reduce the effect of non-flow correlations on the measurement.

The cumulant method measures flow by a cumulant expansion of multi-particle azimuthal correlations, and the flow harmonics are obtained from the cumulant terms of the expansion. The cumulant of the k-particle correlation, called the kth order cumulant, removes the contribution of all lower order correlations and so is expected to remove the effect non-flow correlations between less than k particles. To calculate the cumulant expansion, a generating function of the multiparticle correlations in a complex plane was used. The LYZ method uses the large-order behavior of the cumulant expansion, rather than explicitly computing cumulants at a given order. The flow signal is obtained from the zeros in the complex plane of a generating function of azimuthal correlations.

In both the cumulant and LYZ methods, the feasibility of the measurements is dependent on the magnitude of the resolution parameter $\chi \equiv v_n \sqrt{M}$, where v_n is the harmonic used for integrated flow, or average flow over the measured transverse momentum range, and M is the multiplicity of charged hadrons. Typically, v_n is too small in central collisions, and M is too small in peripheral collisions, making the higher-order cumulant and LYZ measurements challenging under these conditions.

The full details of the implementation of these methods for this analysis are described in references [4] and [10].

RESULTS AND DISCUSSION

The main results of the analysis include: 1) $v_n(p_T)$ at mid-rapidity $|\eta| < 0.8$ for up to 12 centrality classes in the range 0-80%, 2) integrated v_2 as a function of pseudorapidity ($v_2(\eta)$) for 12 centrality classes, and 3) integrated v_n at mid-rapidity $|\eta| < 0.8$. Figures of the complete results and discussion are given in references [4] and [10]. Here, a

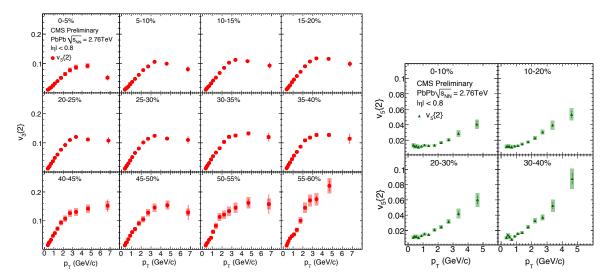


FIGURE 2. Odd harmonics: $v_3\{2\}$ (left) and $v_5\{2\}$ (right) as a function of p_T at mid-rapidity ($|\eta| < 0.8$) for the centrality classes indicated in the figures. The error bars represent the statistical uncertainties, and the colored bands represent the systematic uncertainties.

few of the main results are shown and briefly described.

Figure 2 shows the odd harmonic coefficients measured as a function of p_T in several centrality classes. One notable feature of these results is the weak centrality dependence in both the shape and magnitude of the signals, which is expected if these harmonics are induced by fluctuations in the initial conditions that also have a weak centrality dependence [11]. The p_T dependence of the even harmonics, which are not shown here, exhibit behavior compatible with hydrodynamic flow. The $v_2(\eta)$ results are presented in figure 1 and show only a weak η -dependence, except in the most peripheral events, which are more affected by non-flow correlations. The pseudorapidity dependence may provide constraints on the description of the system evolution in the longitudinal direction.

These measurements taken together may aid in the systematic validation of different approaches to the modeling of heavy ion collisions and lead to a reliable determination of some of the transport properties of the hot QCD matter produced in the collisions.

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